CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

The Virtual Design Team -

Using Simulation of Information Processing to Predict the Performance of Project Teams

by

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Summary

The purpose of the proposed research is to model the verification and coordination processes taking place in design. This model will predict the performance of design project teams using discrete event simulation of their information processing and communication behavior. The output of the simulation will include statistical performance measures of verification and coordination, as well as project duration and personnel cost. The model of verification and coordination processes will use these measures to suggest changes to the organizational structure and information processing tools of the project design team.

The work continues and extends the existing Virtual Design Team (VDT) framework [Cohen 92]. The proposed research links a design team's organization structure and information processing tools to the performance of the design process. Ongoing research in CIFE [Fergusson 92] establishes the relationship between process performance and end-user satisfaction. Together these studies will establish a link between the performance of the design team's organization and the "product quality" of its design outputs.

The simulation variables are a description of information processing tools, rules for information processing, and rules for verification and coordination behavior. A given project is modeled by a "case-specific" description of the project team members, the activity network of the design process, and the requirements to the various activities in the design process. The requirements to these activities are established from the functional requirements of the design solution. Employing Quality Function Deployment [Hauser & Clausing 88] a so-called "QFD House of Quality" is constructed. QFD shows the correspondence between functional requirements and engineering solutions, indicating the complexity of the inspection to verify that the design solution satisfies the requirements.

Motivated by Daetz's [Daetz 90] four-phase model for OFD, another "QFD House of Quality" is used to show the relationship between the solutions and the responsible subteams. Interactions between solutions are shown in the matrix at the "roof of the house" and indicate needed interdisciplinary coordination between subteams throughout the design process. The verification and coordination requirements are used in setting up an activity network consisting of design tasks, verification tasks (within a discipline) and coordination tasks (across disciplines).

Discrete event simulation represents information being processed by the project team to carry out design, verification and coordination activities. Information is transmitted between team members using various information processing tools. The team members select among and respond to incoming communications according to their attention rules, verification rules and coordination rules. These rule-sets embody the project policy for communication and quality assurance.

Failure probabilities for verification and coordination activities are derived heuristically from the indicated verification and coordination needs. Using these probabilities, the simulation produces statistical measurements of verification and coordination failures. In addition the simulation gives estimates of project duration (for the critical path activities) and cost of the design process (the total number of personnel hours). These performance measures are compared with case-specific performance criteria for the project in question. The comparison is used as a measure of the "quality of the design process", and to suggest possible changes to the information processing tools, structure or requirements. This will enable managers to begin "designing" more optimal project team organizations for their design projects.

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Contents

1. Introduction

This chapter gives the motivation, purpose, scope and specific aims of the proposed research. In addition, it contains an outline of the various chapters of the proposal.

1.1 Motivation for Studying the Performance of Project Teams

Inadequate and varying quality accounts for large losses in the construction industry. An interesting question in this connection is why seemingly similar design teams, given reasonably similar budget, schedule and requirements, often perform very differently in terms of cost, timeliness and adherence to schedule requirements. Such differences may in many cases be attributed to the goal and/or environment (such as changing specifications from the client, changing requirements of regulatory control, etc.). There remain never-the-less elements of design team performance which appear to be determined neither by goal nor environment, but by various elements of the technology used by the project team.

The output of any process depends on how the process is carried out, which in turn depends on the abilities of the organization carrying out the process. That is, the input-skills of, and coordination of actors in, the project team determine the output from the project. Thus in the last few decades we have changed the way we think about and handle quality control. From previous concentration on verification of results we now concern ourselves more with verifying the process. Lately also we have started to focus attention on specifying required skills and experience of project participants. This means that we can perform much of the verification "a priori", and thus "catch errors before they occur. " This is clearly more cost efficient since the committed capital cost, the incurred transaction cost, and the cost of monitoring performance are all lower.

However, to carry out this pre-qualification of design teams is by no means easy. A systematic approach to "designing the optimal team" requires powerful methods and tools for studying project teams. An important element of organizational behavior is information processing. Thus motivation for the proposed research is a need for improving the methods and tools we need for concurrently designing the design process and design project team organization.

1.2 Purpose and Scope of the Proposed Research

The purpose of the proposed research is to demonstrate that we can model the impact of information processing and communication on quality of verification and coordination, and thus on design team performance. This rests on an assumption that part of the differences in performance may be attributed to variation in the communication structure and information processing tools available to the team. Communication structure is meant to include both formal organizational relationships, the project team structure, professional (work) constellations and informal social relations. Similarly, information processing tools include a range of tools for sending and transmitting information.

The design process is described as a series of design, verification and coordination activities. Verification is is defined as checking that resulting engineering solutions satisfy specified requirements. The term coordination is used for communication in order to correlate design work and coordinate project progress. The various activities require information processing among the various design team members. The outcome of verification and coordination activities are determined statistically, from associated failure probabilities. These probabilities are set heuristically based on indications of the complexity of verifying requirements and the intensity of coordination among design participants. To get the indications of complexity the functional requirements are used to construct two "QFD Houses of Quality". The first indicates interactions between functional requirements and engineering solutions; the second shows correlation of solutions and responsible project team members.

The performance measures for the design projects are obtained by simulating information processing. The performance of the design team is measured in terms of the number of failures in verification and coordination, as well as by probabilistic duration and cost measures. The performance is compared with the performance criteria for the project, as a basis for changing the information processing structures and tools. Figure 1. 1 summarizes the conceptual model for verification and coordination in design projects.

The specific aims of the proposed research are to
(1) observe the verification and coordination processes of real world design projects,
(2) define a model of verification and coordination in design projects (build a framework).
(3) exercise the model using discrete event simulation (operationalize the framework), and
(4) test the model predictions against established theory and observations (validate the framework).

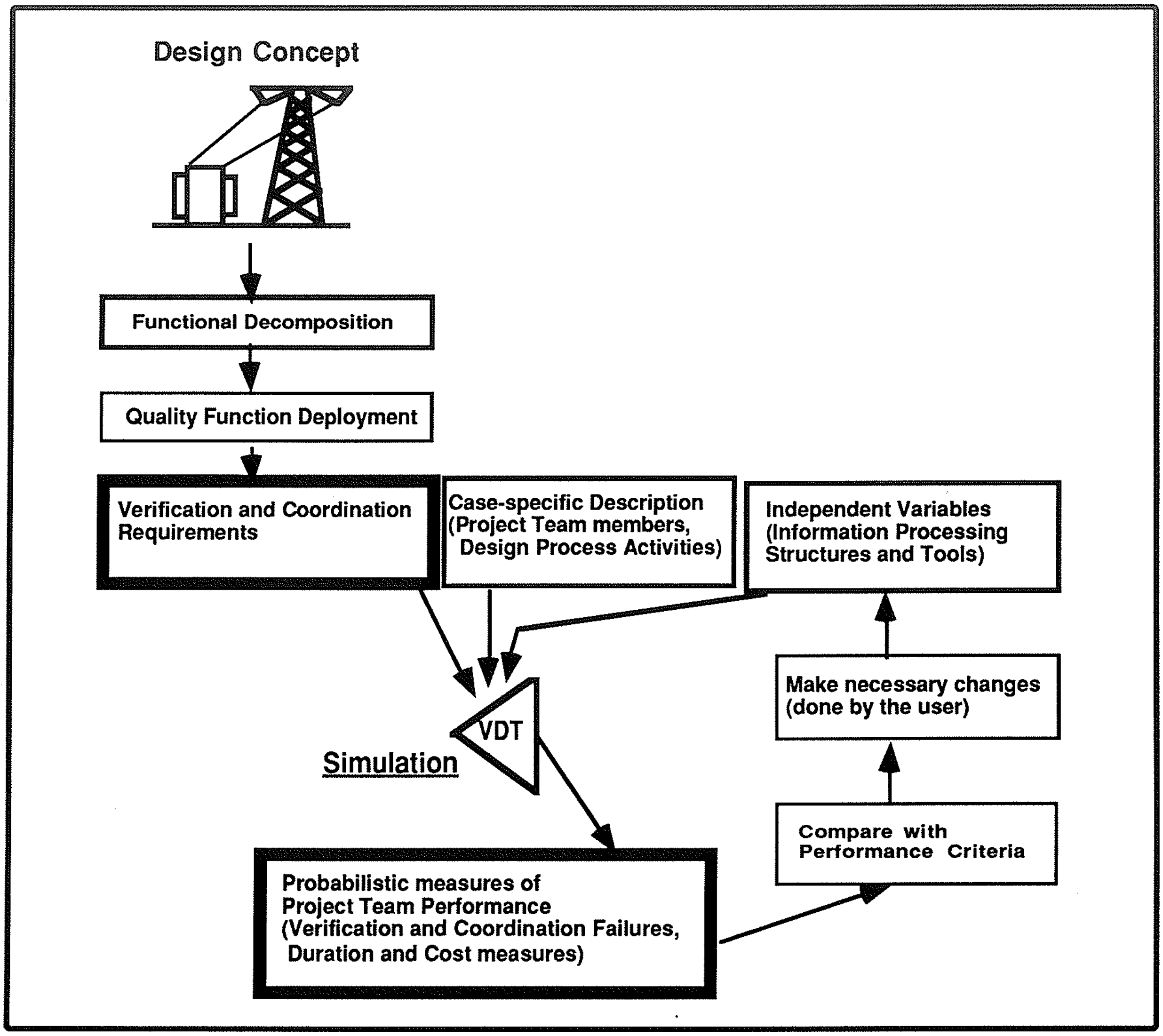

Figure 1.1 Overview of the proposed research

The main parts of the model for verification and coordination processes in design (the contribution of the proposed research) are marked by thick lines

VDT models and simulates information processing in design teams. The performance of the team is measured by duration, cost and the number of verification and coordination failures .
The performance is compared with case-specific performance criteria, as a basis for changing the information processing structures and tools.
The verification and coordination requirements are derived from the functional requirements of the design concept, using functional decomposition and Quality Function Deployment. The simulation also uses a case-specific description of the project team members and the activity network for the design process.

The research scope is determined by Jay Galbraith's model of information processing in organizations [Galbraith 77], and by the use of discrete event simulation. The proposed research builds upon the model established in the Virtual Design Team (VDT) project [Cohen 92]. The proposed research will not develop extensions to organization theory. Another limitation will be the assumption that actors have bounded rationality [Simon 73], excluding individual differences in motivation and irrational behavior of actors. Also, the proposed research is intended to produce qualitative predictions, i. e., it does not address detailed calibration of the model predictions against absolute values of real world measurements.

1.3 Outline of this Proposal

In order to make navigation through this proposal as painless and enjoyable as possible, a set of summary comments for the various chapters is given below. The style of the comments has been kept in the language of Miguel Cervante's' "Don Quixote", an early explorer of human organizations who set out on an improbable journey in quest of the impossible (any further similarity is purely coincidental).

Chapter 1. (the present chapter) is the *Introduction* -
- in which is given an overview of the problem to be addressed by the proposed, and no other, research.

Chapter 2. is *A Critical Review of Past Research* -
- in which is told what has been done so far in the fields addressed by the proposed research, and why this does not satisfactorily solve the problem.

Chapter 3. is the *Research Approach* -
- in which is presented the various assumptions and idealizations to be made in the proposed research, the strategy for representation and reasoning, together with the planned approach to validating the predictions of the research.

Chapter 4. is the *Research Plan* -
- in which is stated the expected rate of progress to carry out and complete the proposed research.

Chapter 5. is *Contributions of the Dissertation* -
- in which is given an overview of the deliverables resulting from the proposed research, and from nowhere else.

Chapter 6. is the *List of References* -
- in which is given a list of readings relevant to the proposed research.

Appendix A contains *An overview of course-work and preparations* -
- in which are described the author's academic preparations for this research, in terms of courses taken at Stanford University .

Appendix B contains *Curriculum Vitae for the Author* -
- in which are summarized the earlier adventures of the author.

2. A critical Review of Past Research

This chapter summarizes work in each of a series of research areas that are relevant to the proposed research. As will be apparent from the discussion, neither field by itself provides the necessary framework for predicting the performance of design teams.

For a number of decades we have seen rapid development in the knowledge and tools for studying the behavior of physical structures. For studying the behavior of organization structures however there has not been a similar advance, and there exist few, if any, practical methods and tools even for organizational analysis, much less for organizational design. This mismatch is illustrated in in figure 2.1 below from [Levitt 91a].

2.1 Organization theory and computer modeling of organizations

A difficulty in studying organizational performance is that it involves so many different disciplines. Since the foundation of the proposed research is on information processing in organizations, we first, in section 2.1.1, review briefly relevant parts of organization theory. Next, in section 2.1.2 we look at the particular field of communication in organizations, and then at the emerging field of coordination theory in section 2.1.3. A review of computer modeling of organizational behavior is given in section 2.1.4. Section 2.1.5 contrasts the current version of the VDT with that resulting from the proposed research. The conclusion from these sections is that there does not appear to be any research so far that explicitly addresses case-specific organizational performance by studying information processing in organizations.

2.1.1 Organization theory

The proposed research is based on organization theory [Thompson 67] . In particular it focuses on how organization structure and communication tools determine the behavior of organizations, and on how managers go about processing their work [Minzberg 73]. The structure of an organization is determined by its goals, environment and technology [Minzberg 83], and its behavior is composed of intendedly rational behavior exhibited by boundedly rational members [Simon 73], [March 88].

Available Methodologies	Physical Structures	Social Structures
Empirical Validation (Trial and Error)	Dwellings, simple fortifications: < 5000 BC	< 5000 BC to present
Qualitative Theory Empirical Validation	Pyramids, temples, fortified cities: 5000 BC to 1800s	Political science, sociology, economics: 1000 BC to 1960s
Mathematical Theory Empirical Validation	Matrix Algebra and Differential Calculus Late 1800s - 1950s	very little work: 1960s to present
Theory Empirical Validation Computer Simulation	Matrix Inversion Finite Element Analysis: 1950s to 1980s	virtually none
Theory Empirical Validation Computer Simulation Automated Synthesis	OOP Design Automation: 1990s -	none

Figure 2.1 Science in design -Physical structures vs Social Structures

Building on a long history of experience and theory-building, the engineering sciences have established qualitative and mathematical methods and tools for analysis of physical structures.
Based on knowledge engineering and computer simulation we are now able to address design automation.
By comparison, our methods and tools for analyzing social structures are far less advanced.
Presently we have no quantitative methods, and no tools for analysis or design of organizations.

An important model of information processing in organizations, in response to uncertainty in technology or environment, was developed by Jay Galbraith [Galbraith 77], who described a set of different mechanisms by which organizations can increase their ability to handle uncertainties, whether by reducing the information flow or increasing the ability to process information.

While neo-classical organization theory has advanced our understanding of organizations considerably, it has only addressed the organizational effects of modern information technology to a limited extent. Recent work in studying the impact of electronic mail [Rice 90], computer use in work groups [Gutek 88] and knowledge based systems [Wooldridge

91] appears to be in the formative stages, and only tentative frameworks are available [Hauptman 87], without empirical investigation and comparison [Huber 90]. Recent work on networking organizations [Savage 90] and [Grenier 91] provide speculations about the impact of information technology in organizations, but is not operationalized for computer modeling or empirical studies.

Because the field of relevant research is so wide, only a brief outline of the most salient work is included. For a thorough review of the literature on organization structure and behavior the reader is referred to [Cohen 91] and [Levitt 91b].

2.1.2 Communication in organizations

The mathematical theory of communication was laid out by Claude Shannon [Shannon 62]. The basic idea is the use of a message transmitted from an intelligent sender to an information transmitter (encoding tool), signals flowing between transmitting and receiver (decoding tools), and the decoding tool delivering the message to an intelligent destination. The signal may be disturbed by noise, introduced by noise sources. This model of communication, without the addition of a separate noise source, was adapted for the present version of the VDT [Cohen 92].

In a review paper on emerging theories of communication in organizations Fulk&Boyd [91] note the lack of a unifying theoretical framework and strongly advocate the need for promulgating new theory. They outline areas of theoretical development, resting on four perspectives: mechanistic, psychological, interpretive-symbolic and system-interactionist. These areas are

- Communication Media Choice, including the media richness model and the social influence model of technology use.
- Information Processing and Organization Design, focusing on organization design and decision-making.
- Information Processing Technology-Supported Decision Making Groups, including Group Decision Support Systems (GDSS), Computer Supported Cooperative Work (CSCW) and the theory of Adaptive Structuration.
- Network Theory and Network Analysis.

These areas have a common concern with information processing in organizations. Particularly the first three are relevant to the proposed research. It is somewhat disquieting therefore to note the authors' lamenting of the lack of coherence in theoretical approach and research effort. Moreover, it appears that work in these fields has not so far addressed issues concerned with performance of organizations.

2.1.3 Coordination theory

The emerging field of coordination theory [Malone 91] has addressed issues relating to inter-disciplinary coordination, extending ideas about coordination from computer science, organization theory, operations research, economics, linguistics and psychology. An interdisciplinary approach to studying cultural and structural issues of communication in organizations, as well as a focus on operationalization, makes this a promising area for studying organizational performance.

Crowston [Crowston 90] discusses an information flow model of coordination in organizations, and describes the basis for a computer tool to simulate organizations based on distributed artificial intelligence. No work so far has specifically addressed the relationship between communication resources (organization structure and information processing tolls) and organizational performance.

Studies in the field cover a range of interesting perspectives and applications, including management of organizational interdependence [Rockart 89], studies of the relationship between information technology, capital and firm size [Brynjolfsson 89], a structuration approach to the interaction between technology and organizations [Orlikowski 90], and new managerial working styles [Brynjolfsson 91]. Also, a series of prototype systems addressing different aspect of organizational coordination have been built, including Object Lens (a spreadsheet for cooperative work) [Lai 88], Sibyl (a decision Rationale Management system) [Lee 90], and CIS/TK (ToolKit for composite information sources) [Madnick 90]. These studies and prototype systems address a series of different problem areas. There does not yet appear to be a unifying theme or theoretical foundation in the field of coordination theory.

2.1.4 Computer modeling of organizations

An early computer tool for studying organizational decision making was an implementation of the garbage-can model of organizations [Cohen 72], based on the idea that organizational decision making is made up by random streams of problems, solutions, choices and decisions. This was later made into a simulation model [March & Olsen 86], which triggered a series of research efforts, as well as development of several related systems. An extensive overview of these and other research and development efforts is provided by Masuch and LaPotin [Masuch 89].

Another early system for simulating organizations was Arousal (A Real Organization simUlated As Life) [Lansley 86], which was used as a simulator to train managers in the art of decision making. However, since its system model was compiled into executable code it lacked transparency for understanding the theory and assumptions that guided its behavior, and thus learning was only possible by experimentation. Moreover the system considers individual decision making, and thus take only limited account of organizational interaction.

Organizational studies using operations research [Burton 84] provides a framework, and a series of implementations for studying decision making and coordination. However, all of these systems are based on a continuous problem space description of the variables, and are thus restricted to numerical interval or ratio measures [Babbie 86]. Thus these systems fail to give the necessary expressive power for modeling and reasoning about complex organization structure and behavior.

Use of discontinuous problem space representation and heuristic reasoning in modeling organizational structure and behavior was introduced by doubleAISS (Actors, Actions, Skills, Structure and Issues) [Masuch 89]. doubleAISS models decision processes of organizational actors by simulating the behavior of a generic organization. The simulation gives the functional change of various parameters such as cognitive capacity, commitment, workload and aspiration. The output measures include productivity, number of solutions, non-solutions and non-decisions reached in the simulation, and the organizational climate. Thus, doubleAISS has a number of features of interest to the proposed research, including measures of organizational performance. However, it does not model real organizations, nor the content of work tasks.

In a series of simulation studies, researchers at Carnegie-Mellon University have studied organizational decision-making and performance issues of cooperative problem-solving [Carley 90 a]. The study involves the effects of task complexity and information redundancy, and measures performance by learning rates. However, the simulation only involves a simple synthetic task (determining the 0's and 1's in a binary number).

An illustration of the above discussion of relevant work in the area of organizational modeling is summarized graphically in figure 2.2, with an attempt to indicate which effects are considered and omitted in the various models.

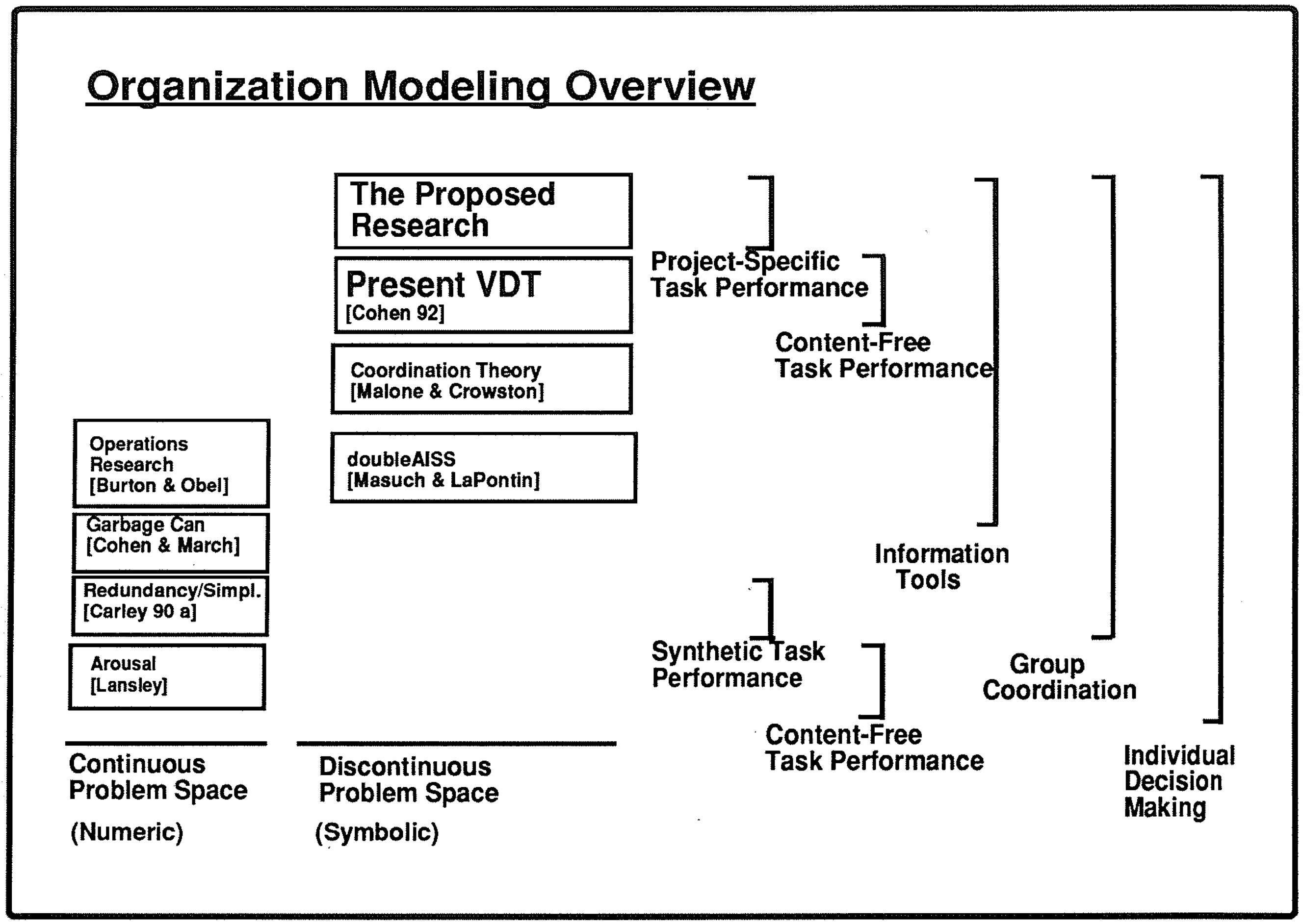

Figure 2.2 Organizational Modeling Overview

The figure gives an overview of important efforts in computer modeling of organizations. Two groups of tools are distinguished, those based on a continuous problem space description, and those based on a symbolc description. The tools are classified according to which effects are included in their models. As shown, only the proposed research explicitly addresses content-specific organizational performance.

2.1.5 The current version of the Virtual Design Team

The current version of the VDT [Cohen 92] models organization structure and information processing tools as independent variables (input) to the simulation model. The theoretical framework for the VDT implementation is based on work by Galbraith on information processing in organizations [Galbraith 77], and by Minzberg on managerial work [Minzberg 83]. The input description also includes design tasks and design team actors (the project manager, design manager, subteam managers and subteams).

The VDT uses discrete event simulation of information processing. The actors receive, process and transmit communications according to rules. Information arriving at each actor is placed in an "in-tray" (metaphor for queue of incoming communications) waiting to be processed. The actors prioritize and select among incoming communications stochastically, using attention rules.

The results (output) from the simulation are measures of activity duration as well as total project duration. The latter is found by summing activity durations for activities on the critical path. The results of the VDT agree qualitatively with predictions from Galbraith's work [Galbraith 77], based on observations of real life design teams.

However, the current version of the VDT does not include design requirements in the description of design tasks (why they are performed), nor the solutions they are meant to produce. Thus the results from the simulation are limited to content-free measures of duration as a performance indicator (see figure 2.2). The proposed research will build on the existing framework and prototype implementation of the Virtual Design Team (VDT), but extend it to include descriptions of design requirements and solutions in terms of verification and coordination requirements in the design process. This difference is illustrated in figure 2.3.

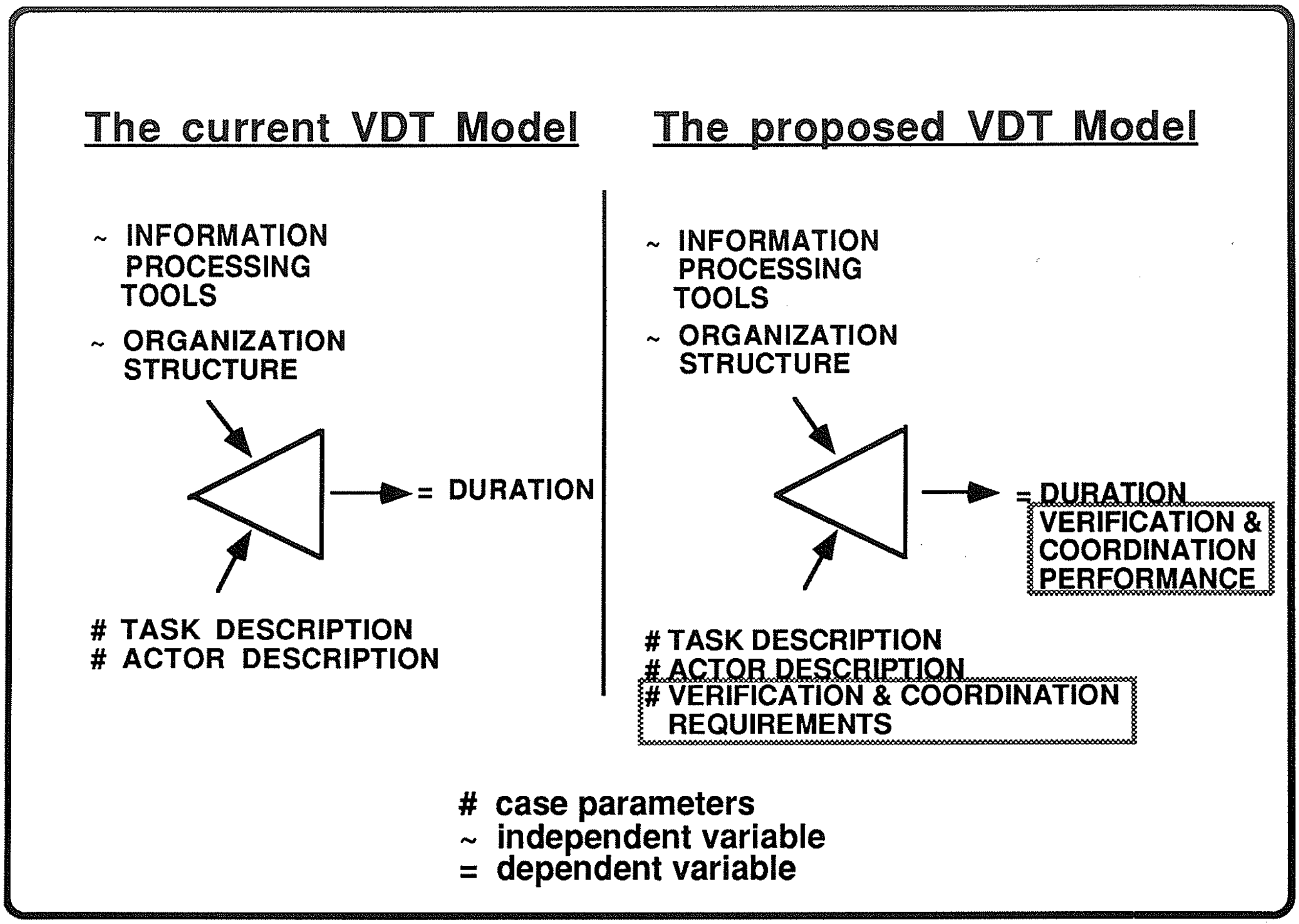

Figure 2.3 Contrasting the current VDT model with the proposed research

In the current VDT simulation model [Cohen 92], the decription of design activities is "content-free"; i.e. not related to the project-specific design requirements. Thus, the simulation results are limited to duration and cost measures. In the proposed research, the input description will be augmented by a description of project content, in terms of the verification and coordination requirements of the design process, derived from the functional requirements of the design product. This allows for reasoning about the (verification and coordination) performance of the design team.

2.2 Modeling of design requirements and design team performance

Since we are concerned in this study with project design teams, and wish to introduce a description of the specific requirements of design tasks into the simulation model, it is necessary to consider different perspectives of information modeling and performance evaluation. First, the introduction of design (product) requirements makes it necessary to review the state-of-the-art of information modeling in section 2.2.1. Next, we summarize different views of the design process in section 2.2.2. Then, in section 2.2.3 we review different approaches to the modeling of quality. Finally, to operationalize the model, we consider in section 2.2.4, issues of knowledge engineering and simulation.

2.2.1 Information modeling of products

Fundamental to the proposed research is the idea of models to describe the many different aspects of the real world. Marvin Minsky in his book the "Societies of Mind" [Minsky 86], argues for the power of redundancy, and of the multiple meanings of things. This is reflected in information models using product, process, and resource dimensions to describe various aspects of the world [Syvertsen 91], and in the use of multiple information structures to describe various aspects of engineering products, processes and organizations [Lillehagen 91]. Examples of such structures include requirement structures, cost structures, performance structures and support structures.

In the modeling of products much progress and clarification has been made within the Standard for the Exchange of Product Model data (STEP) [IGES/PDES 91]. An important conceptual contribution to the development of the STEP standard has been made by the ongoing research program at the Technical University and TNO in Delft, Holland. The contributions include the General AEC Reference Model (GARM) [Gielingh 88b], [Tolman 89] and the use of functional decomposition networks for product modeling [Willems 88]. A simplified example of the use of functional decomposition for an electrical substation is given in figure 3.1.

Another example of recent work on integrative product and process modeling in the AEC industry includes development of a life-cycle integration framework [Fischer 92]. However, all of these efforts focus on products and processes. None of them explicitly address how organizational structure and tools affect the performance of those products and processes.

2.2.2 Design and information processing

In order to study information processing of design teams it is useful to summarize the various possible views of the design process, and also to review design research relevant to the proposed research. Much of the design research to date has been concerned with specific product design cases, and focuses on how we can improve their design process.

An example of a structured tool for describing and simplifying the design process is the design structure matrix for representing the interrelation between complex design tasks [Whitney 90]. Louis Bucciarelli [Bucciarelli 88] takes an ethnographic perspective on design (design as a social process) and points to the relation between product requirements, design tasks and design team.

Herbert Simon in his book "Sciences of the artificial" [Simon 69] distinguishes between the natural, artificial and synthetic, and argues that "synthetic is often used in the broader sense of designed or composed", and that "we speak of engineering as concerned with synthesis". This extended view of the design process is taken by [Holt 90] who distinguishes between (1) design as a problem solving process, (2) design as a creative process, (3) design as a need fulfilling process, and (4) design as a human activity process. A similar view is taken by [Klingsheim 90] in arguing that formal theories of the design process are needed to face the challenge of managing concurrent design projects. Initial attempts to formulate unified formal theories of design are summarized in [Whitney 90] and [Gebala 91].

A number of researchers have developed theories, and built systems to investigate how modern information technology may advance product design. Recent applications of information technology to describe various aspects of the design process include applications of knowledge-based systems applications in engineering design [Sriram 90], knowledge-based management of concurrent engineering [Salzberg 90], [Eppinger 91] and [Levitt 91c], and application of shared work-spaces in computer aided collaborative product development [Sriram 91]. However, the latter efforts have been oriented towards automating the design process, rather than studying information processing in design.

2.2.2 Modeling of quality

In an attempt to define a general classification framework for quality, Garvin introduced five approaches to the definition of quality [Garvin 84]

(1) the transcendent approach of philosophy,
(2) the product-based approach of economics,
(3) the user based approach of economics, marketing and operations management,
(4) the manufacturing based of engineering departments, and
(5) the value-based approach of operations management.

While all of these views may be valuable in the context of the proposed research, they are hard to operationalize. A more useful approach is the concept of Total Quality Management (TQM). Here quality is viewed as a multi-dimensional measure of the match between customer expectations and product delivery [DNVC 91]. This may be extended to cover all aspects of product design, construction, operation and support, but is also somewhat difficult to quantify.

While the quality research serves as an interesting source for thinking about performance, as far as the author is aware, no work exist where the above ideas about quality have been applied to monitor the quality of organizations. However, current views of quality seem to be shifting from the traditional "product view" to a more process oriented viewpoint, and recently also towards pre-qualification (quality assurance of) organizations in advance of contract award [DNVC 91].

A useful tool for representing quality-related issues is the functional decomposition by the Functional Unit/Technical Solution (FU/TS) technique [Willems 88]. This is used to derive functional break-down structures by iteratively describing higher level requirements (technical units) and their corresponding technical solutions. The decomposition is performed iteratively, starting from the top-level product requirement, and detailed to derive characteristics (and corresponding specifications) which describe "designable" or "procurable" items.

Another structured technique used in product development is Quality Function Deployment (QFD) [Hauser 88]. Through the construction of a so-called "house of quality", customer requirements are mapped to engineering characteristics and specifications producing relationship and interaction matrices. Figure 3.2 gives an example of a QFD house of quality for an electrical substation. An outline of the use of QFD for all phases of the product development process is given by Daetz [90], where specifications of results from one "house" (phase of the life-cycle) are used as input to the next. This idea is utilized in constructing the second house of quality in figure 3.3.

Ongoing research within CIFE [Fergusson 92] establishes the relationship between project integration (process quality and customer satisfaction (product quality). This serves as an interesting complement to the proposed research, which sets out to establish the link between communication resources (organization structure and information processing tools) and process quality (of verification and coordination).

2.2.4 Knowledge engineering and simulation

Of great relevance to the proposed research are recent developments of powerful knowledge engineering environments. Of particular importance to the proposed research are object oriented programming and model based reasoning [Kunz 88] and [Ten Dyke & Kunz 89]. Thus knowledge engineering now provides tools which allow representation of, and reasoning about, complex behavior of products, processes and organizations.

Similarly, tools for simulation have also benefited from the ability to use symbolic modeling and discontinuous problem spaces to represent nominal or ordinal simulation variables [Babbie 86]. This allows for a much richer description of the simulated environment than was previously possible using traditional numerical simulation tools, with a continuous problem space description in terms of ratio or integer variables.

A recent advance in artificial intelligence is distributed AI (DAI), and the agent paradigm, in which autonomous agents (programs) cooperate in distributed problem solving [Jin 92]. Agent programming allows computers to simulate cooperative problem-solving by intelligent actors, and represents a powerful tool for collaborative work and coordination research. Typically, the problems addressed are complex, and involve highly detailed problem descriptions. However, the scale of the problems considered so far has been limited to "toy problems". This limitation is set by both modeling time and computer power. Figure 2.4 contrasts the current VDT and proposed research with DAI using the dimensions of problem content (detail in the description of the design problem) versus problem scale (size of the organization modeled).

Using the Soar architecture Carley et al [Carley 1990 b] developed Plural-Soar for studying distributed problem solving by intelligent agents residing on different networked machines. The problem studied, the warehouse task, involves locating items on stacks to fill orders according to customer specifications.

While this area of research is still in its initial phases, it may be a powerful environment for future implementations of the tools for organizational modeling and simulation.

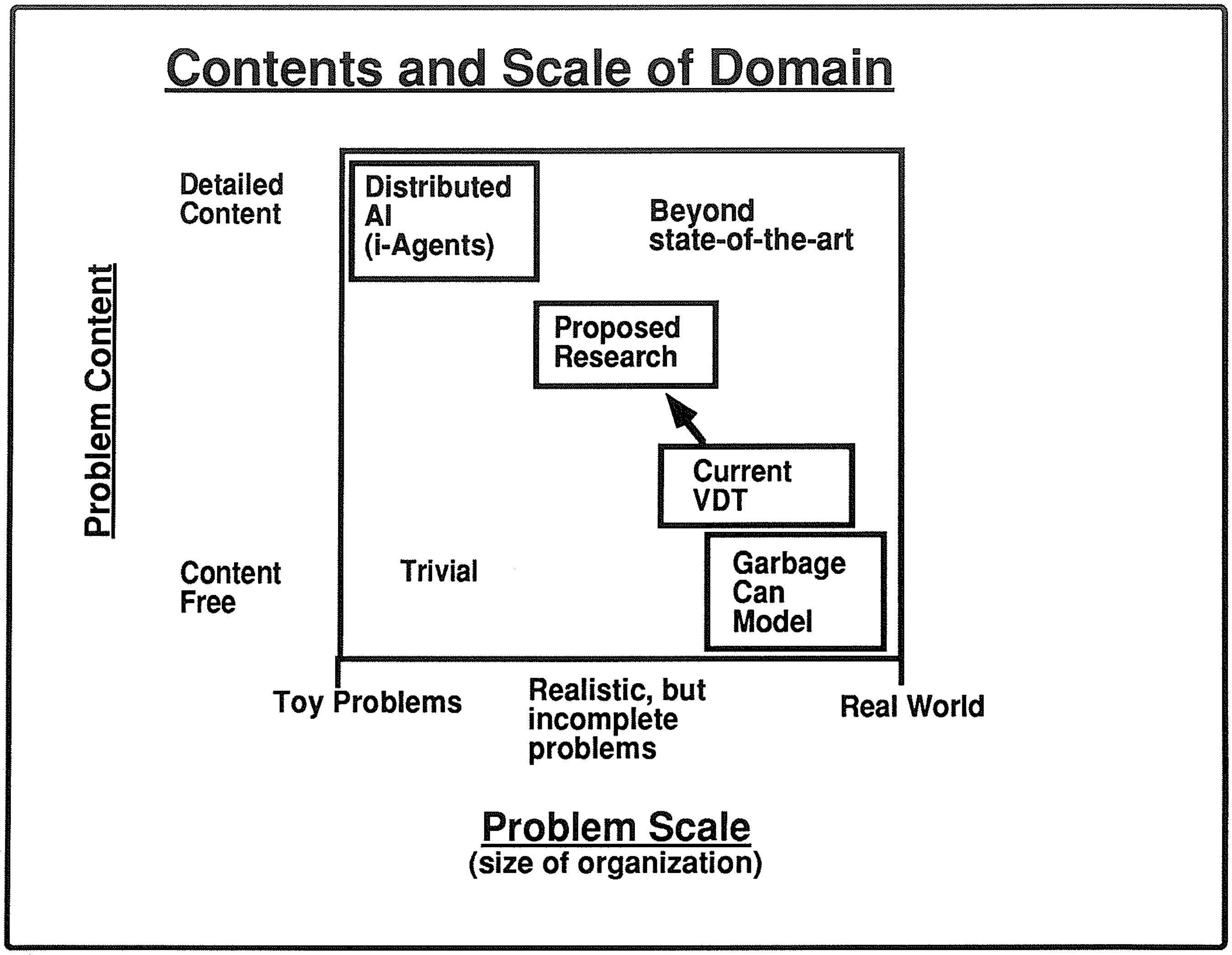

Figure 2.4 Contrasting the current and proposed VDT models with distributed AI and the Garbage Can Model of organizational decision making.

The scale of organizations addressed in distributed AI so far has been limited by the modeling effort, since they require a very detailed description of the organization and problem contents,.
The Garbage Can model [Cohen 72] uses a very simplistic description of the organization and does not describe problem content, and may thus be used to study large-scale organizations. Distributed AI [Jin 92] on the other hand, typically involves a very detailed description of the problem domain, and has so far been limited to studying small scale "toy" problems. The proposed research is an effort to bring slightly more content into the current VDT model [Cohen 92]. This will mean that the scale of project teams studied is likely to be somewhat smaller.

3. Research Approach

This chapter describes the conceptual model of verification and coordination in design projects outlined in figure 1.1 above. First section 3.1 describes the conceptual model. Then sections 3.2 and 3.3 will outline the representation and reasoning of a model implementation. Finally section 3.4 describes the suggested approach to validating and testing the model and implementation.

3.1 A model of verification and coordination in the design process

The conceptual model is built around simulating information processing in design teams. The performance of the design team is measured in terms of failures in verification and coordination, as well as probabilistic duration and cost measures. The term "verification" means to verify that resulting engineering solutions satisfy specified requirements with respect to functionality, budget and schedule. The term "coordination" is used to mean communication in order to correlate the work of the various subteams and managers, and coordinate project progress. Failures occur in verification when the design solutions do not meet their specified requirements, and in coordination when the required attendants are not present.

The functional requirements of the product are derived using functional decomposition [Willems 88]. Starting from the top-level functional requirement, the corresponding engineering solution is described. This solution gives rise to a number of more detailed requirements, which have their solutions. This functional break-down of requirements and matching with solutions is continued to a sufficient level of detail. The solution is then translated into a set of specifications for a procurable or manufacturable component. See figure 3.1 for an illustration.

The model postulates that the difficulty of design verification depends on the number of interdependencies between the different requirements and solutions of the design. Quality Function Deployment (QFD) [Hauser & Clausing 88] is used to illustrate the verification process, in terms of all verification "items" and their interaction. A so-called QFD House of Quality is constructed which shows the correlation between design requirements and engineering solutions, and the interactions between the various solutions. These interactions indicate needed verification activities. This is illustrated in figure 3.2.

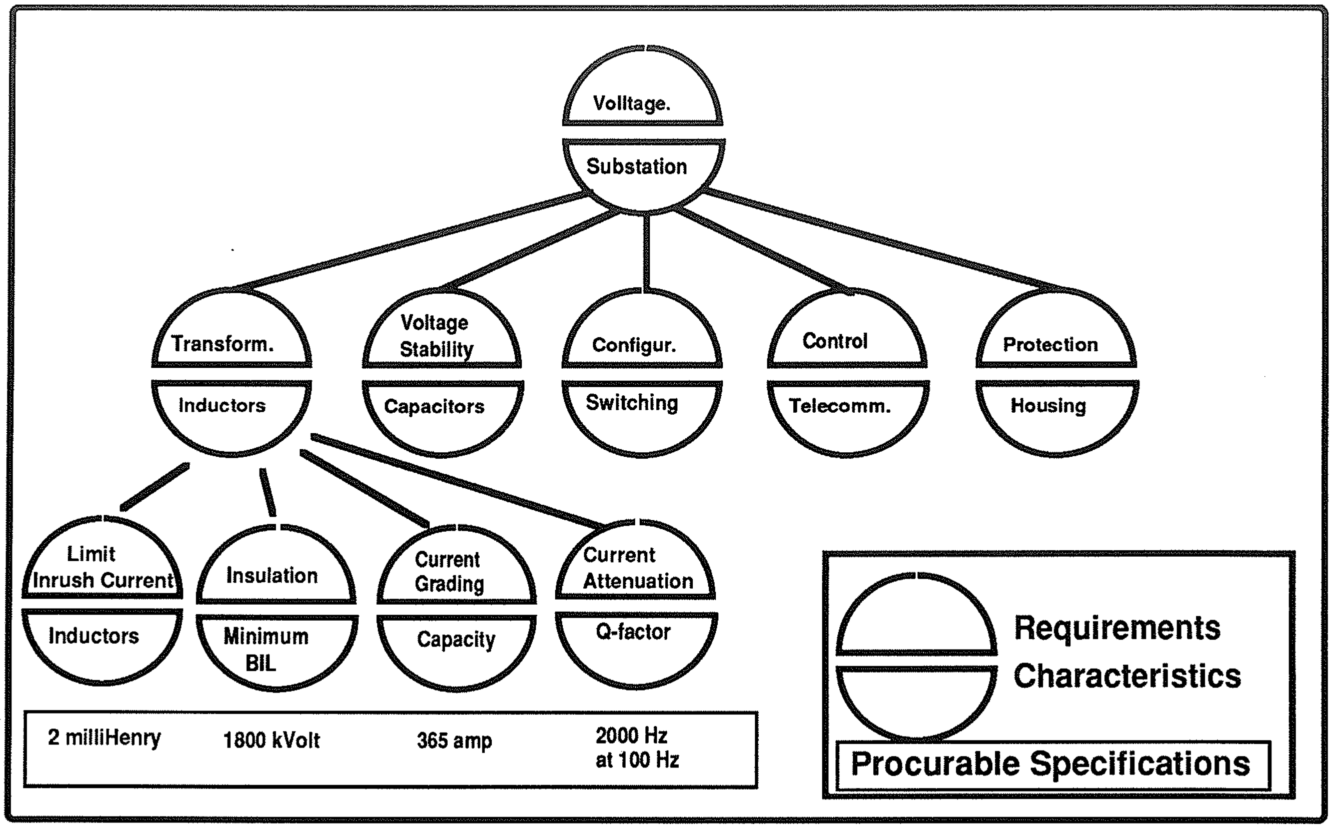

Figure 3.1 Functional break-down structure for part of an electrical substation

The figure shows how a Functional Unit/Technical Solution (FU/TS) diagram [Willems 88] may be used for functional decomposition. The top-level requirement of the design concept is matched by a corresponding technical (engineering) solution. The solution gives rise to more detailed requirements, which have their own solutions (and give rise in turn to more detailed requirements). This iteration is continued until sufficient level of detail has been specified, and the detailed solutions are translated to specifications. The example used is an electrical substation. The functional decompostion has been detailed to the necessary level for procurement of the main inductors.

Likewise the model postulates that the difficulty of coordination depends on the number of disciplines (subteams) involved in designing the different solutions. Another QFD House of Quality is constructed to show the relationship between the solutions and the corresponding technical disciplines or subteams, and indicates the needed set of coordination activities between project team members. This is illustrated in figure 3.3.

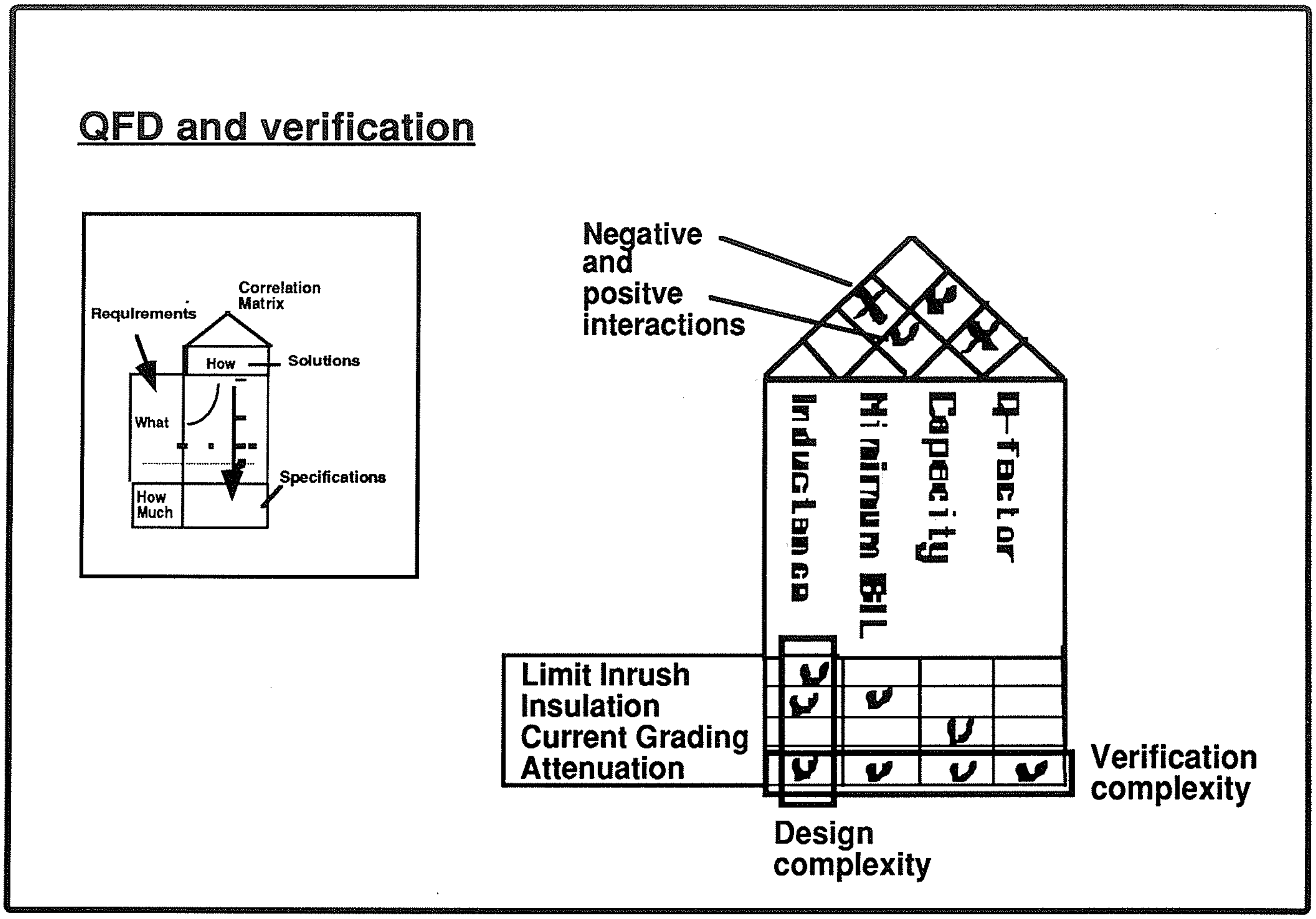

Figure 3.2 Using Quality Function Deployment to get an indication of the complexity of verification

The House of Quality maps correspondence between requirements and solutions in the relationship matrix. The "width per row" of the relationships in this matrix (the number of solutions affected by one requirement) is a measure of the complexity of verifying satisfactory fulfillment of that requirement.
Likewise, the "height per column" of the matrix (the number of requirements influencing a given solution) is a measure of the complexity of the associated design activities.
The matrix at the "roof of the house" indicates negative (x) and positive (v) interactions between solutions.

The required verification and coordination is used in setting up an activity precedence network consisting of design, verification and coordination activities. The various verification activities have associated probabilities of failure. The failure probabilities are determined heuristically based on the indications of verification and coordination complexity from the QFD matrices. The outcome of coordination activities is determined by the degree of attention from relevant members of the project team. If the coordination is attended by all involved, the coordination is

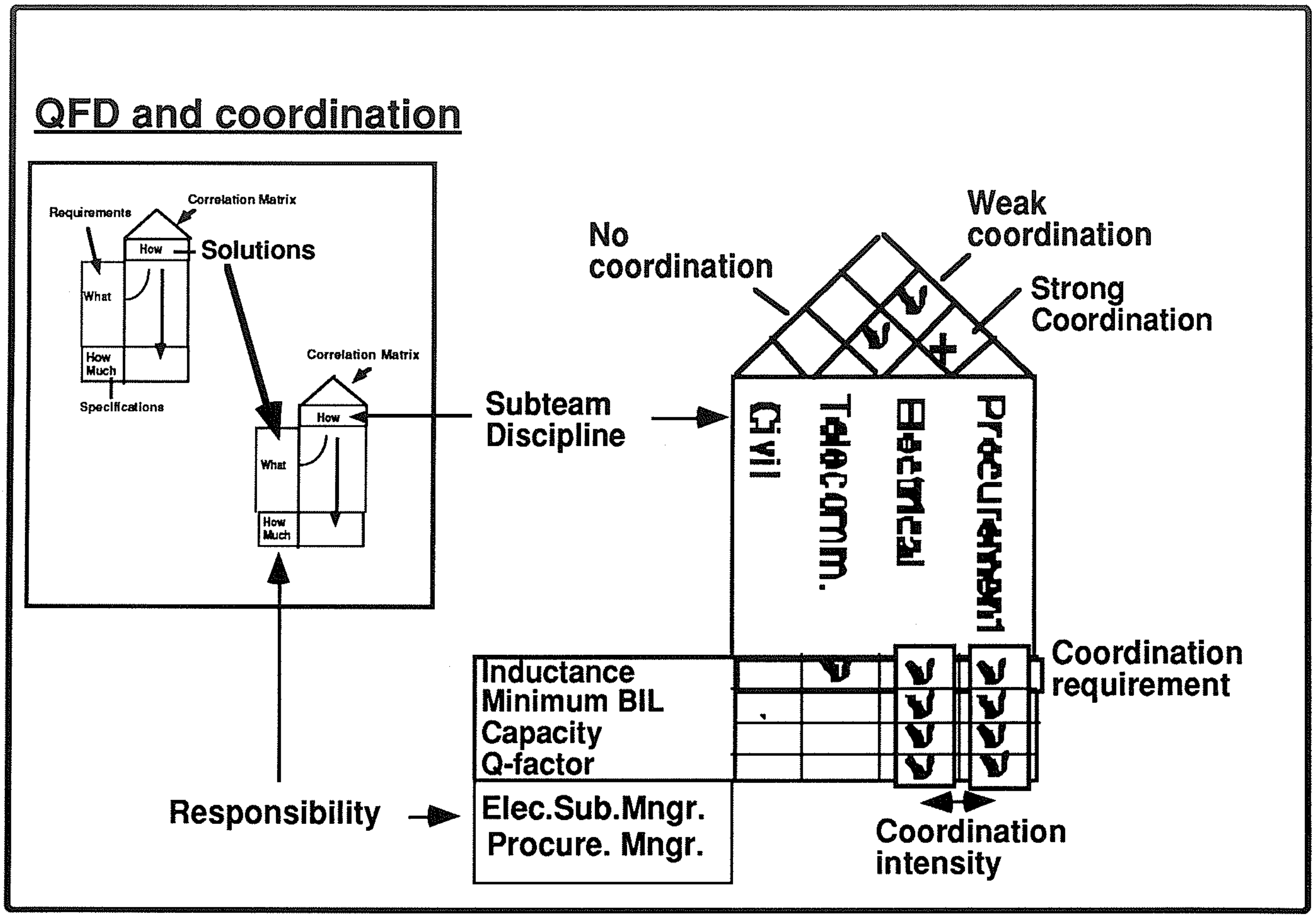

Figure 3.3 Using Quality Function Deployment to get an indication of the complexity of Coordination

The House of Quality maps correspondence between engineering solutions and discipline subteams. The "width per row" of the relationship matrix (i.e. the number of subteams involved in one solution) is a measure of the degree of coordination required for the associated design activities. Likewise, the "height per column" of the matrix (i.e. the number of solutions influencing a given subteam) is a measure of the intensity of the coordination process within that subteam (which is included under "verification"), and between subteams (which is included under "coordination"). The interactions in the matrix at the "roof of the house" indicates needed coordination activities between team members throughout the design process. The number of these interactions is a measure of the coordination complexity, and give the required level of coordination between various subteams and subteam managers.

assumed to be successful. If a coordination activity is not given attention by one or more actors, coordination is less successful. The model has project specific organizational rules for verification and coordination, similar to the organizational rules for attention in information processing. These rules will determine possible actions in the case of non-conformances (verification failures). The actions may be to perform corrective action (re-work) or ignore the non-conformance (carry-on with the next task). Re-work will require additional effort by the design team, and thus be detrimental to the project economy. If the failed activity is on the critical path the re-work will also cause delays relative to the project schedule. In the cases where verification is ignored there will be a higher probability of further verification failures downstream.

Similarly, in the case of coordination failures the choice will be whether to reschedule or ignore the coordination. Rescheduling the coordination has the same effect as re-work in the case of verification failures. If coordination is ignored this will result in lower efficiency of the project team, and also increase the probability of verification failures downstream.

The simulation gives measures of project team performance in terms of total number of verification and coordination failures. This is interpreted as a measure of overall design process quality. The results also include distributions of failures for the various tools, actors and requirements. These failures will identify problems in information processing resources and behavior. Repeated failures of actors and tools indicate insufficient resources or problems in the organization structure (overloading actors relative to their processing ability). Failures for given requirements indicate that the project team does not possess the required tools or structure for these requirements (the functional requirements result in overly complex verification and coordination requirements).

In addition the simulation also gives probabilistic measurements of project duration (the duration of all activities on the critical path, and cost (the total time taken by all activities). The simulated project performance is compared with the schedule, budget and quality objectives (acceptance of non-conformances). Different information processing tools and communication structures are simulated, in order to study the changes in project team performance. The expected observation is a trade-off between quality, duration and cost. This is illustrated in figure 3.4.

For a given design project there will be a "performance envelope" of acceptable outcomes (boundary conditions), set by the budget, schedule and objectives of the project. Changing the organizational policies will affect when to do re-work or ignore non-conformances, and when to reschedule or ignore failures in coordination. This will facilitate observing the required changes to technology and tools in order to keep the project within the performance envelop. The proposed research will focus on manual correction to study the "open loop behavior" of the system (i.e. the user makes changes following completed simulations). However, future extension may include changing these policies during the simulation in "closed loop feedback" (i.e. the system makes changes during simulations). This would change the study from from pure boundary value description with fixed independent variables to an initial value problem where the independent variables (structure and tools) may change as the project progresses.

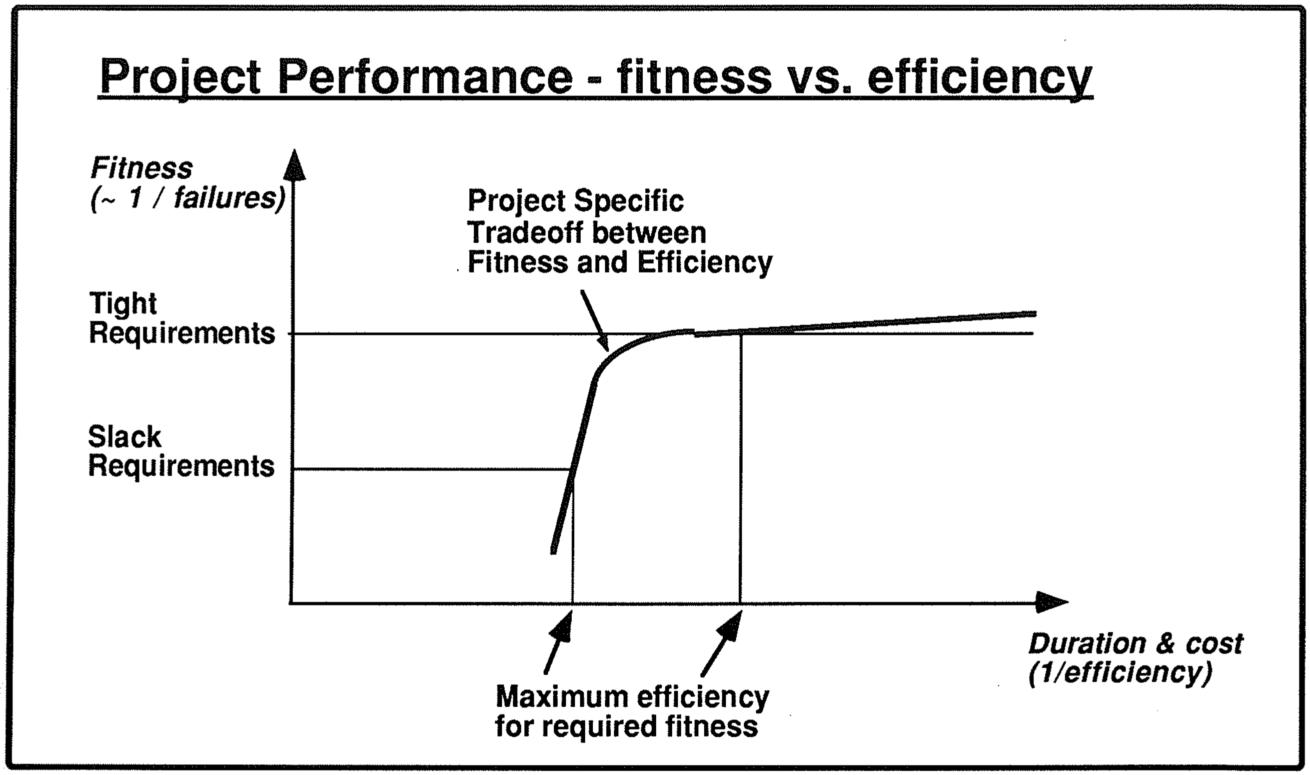

Figure 3.4 Trade-off between project performance measures

In design projects there will typically be a trade-off between efficiency (measured in the current model by the cost and duration) and fitness (measured by the number of failures in verification and coordination). Thus, for a given set of functional (fitness) requirements there will be some maximum efficiency.
The number of failures to verify and coordinate may be minimized by allowing longer project duration (creation of slack resources). As the project duration is shortened by taking out slack from the project schedule, the number of failures will increase.
We may think of quality as an agreement between the client and contractor on the trade-off between fitness and efficiency. (The shape and position of the curve is only meant as an illustration).

3.2 Representation of information processing in organizations

The representation of information processing determines the needs for discrete event simulation. In the simulation environment items are processed by servers to simulate information processing. These items represent objects of communication being passed between project team members. The items are generated by sources, flow through the system of servers and queues, and are destroyed by sinks. The servers represent design team members such as the project manager, design manager, subteam managers and entire subteams (actors). Each actor has an "in-tray" and an "out-tray", which serve as queues holding incoming and outgoing communications. The simulation environment includes a calendar for scheduling upcoming events, and a clock for recording time. The actors receive, process and transmit information, using various information processing tools to encode and decode the actual signals. This is illustrated in figure 3.5 (adapted from [Cohen 92]).

The design process is composed of design, verification and coordination activities. These activities require information processing among the various members of the design team. The outcome of verification and coordination activities is determined stochastically, from associated failure probabilities for individual activities. These failure probabilities are set heuristically by the indicated complexity to verify requirements and coordinate among design participants. The model includes attention rules, verification rules and coordination rules, reflecting the organizational policy governing the information processing behavior.

The project team is described in terms of actors representing the project manager, design manager, subteam managers, design subteams, and external client. The communication patterns of actors are governed by the organizational hierarchy and other organizational structures. The organizational hierarchy is modeled as a set of roles, with authority and skill requirements. These roles are filled by actors, who have skills and experience, and who are assigned responsibility for various activities.

The various activities are connected in an activity precedence network of tasks for processing communications relating to design, verification (within subteams) and coordination (between subteams). The activities and associated communications have attributes describing their requirements and solutions (why and how they are performed).

The value of these attributes is determined by the functional break-down structure and QFD houses of quality. Also the tasks will have attributes describing required authority and skills, and the resulting responsibilities, for the various design, verification and coordination activities. These requirements are associated with roles in the project team organization. Individual or subteam actors fill these roles. This is illustrated in figure 3.6.

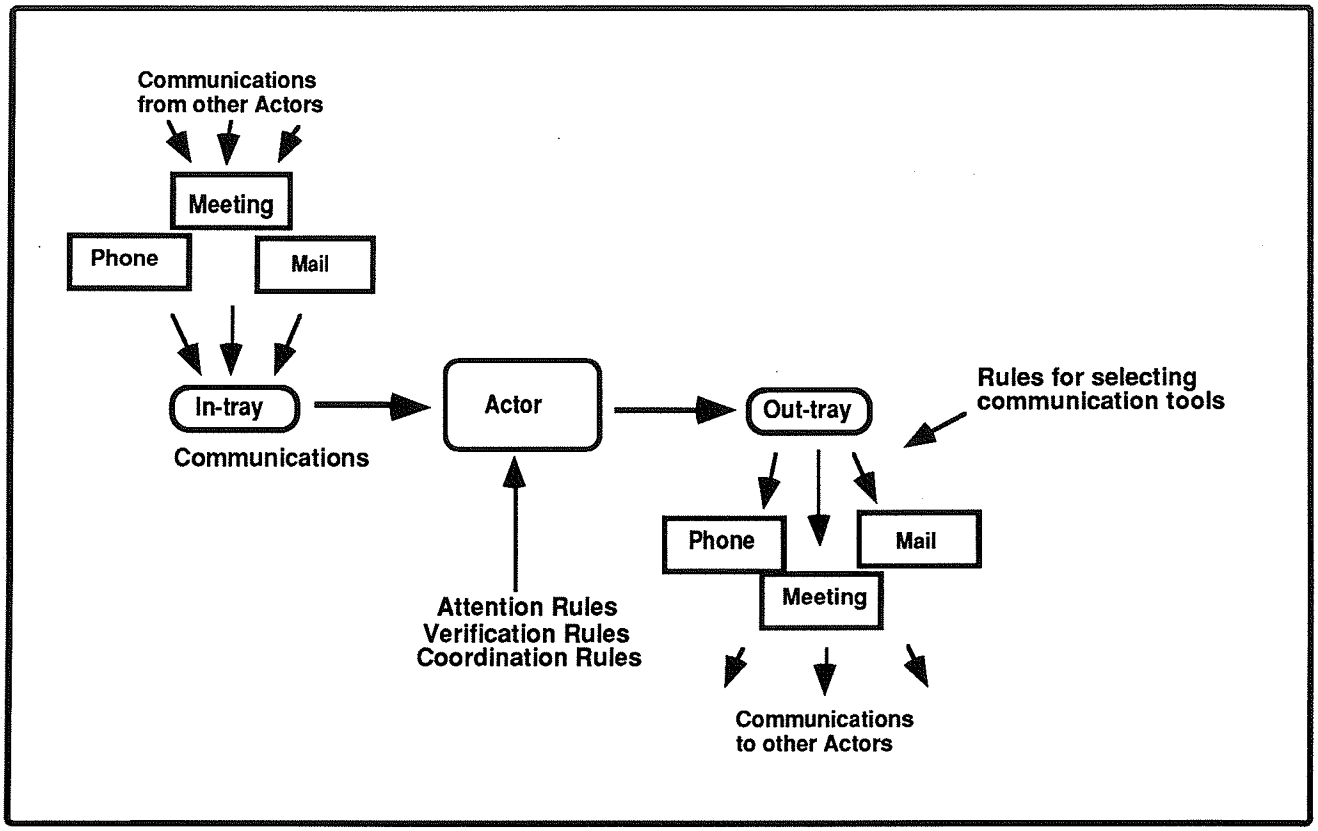

Figure 3.5 An information processing model of design team performance (from [Cohen 92])

Communications of different types arrive in the "in-trays" of actors, and are processed according to attention rules and actor preferences. Communications are transmitted between actors by appropriate information processing tools (e.g. memo, fax, CAD-file, e-mail, voice-mail, telephone, video-conferences and meetings). Each communication has a sender, a recipient, a copy-list and a priority, as well as a so-called natural-idiom. The natural idioms are text, graphics, (telephone) conversation and face-to-face meetings.

In the present VDT model [Cohen 92] tools are described in terms of dimensional attributes such as natural idiom (text, graphics, voice etc.), synchronicity (synchronous, asynchronous), capacity, bandwidth, recordability (recordable, unrecordable), cost of use and proximity (to the user).

Actors have preferences for tools and natural idioms, and are guided in their information processing behavior by rules for allocation of attention, verification procedures and coordination behavior.

3.3 Reasoning about the performance of design teams

The various incoming communications can be part of design, verification and coordination activities. Upon arriving in the in-tray of project team members communications require attention from recipients. As the simulation proceeds the various team members and subteams must make decisions about selecting among communications from their in-trays.

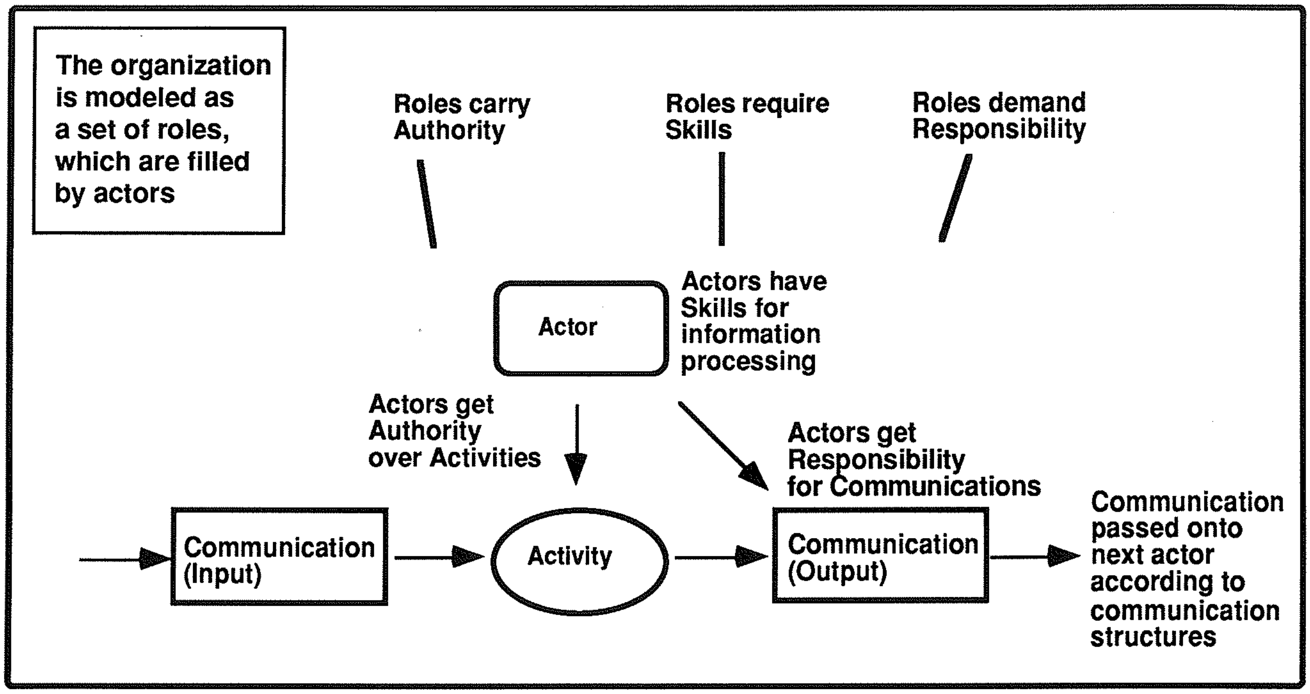

Figure 3.6 Organizations consist of Roles filled by Actors

The design process is carried out by a project team, made up by the project manager, design manager, subteam managers and subteams.
The organizational hierarchy is defined by "Roles", which have associated authority, required skills and responsibility. These roles are filled by actors who (ideally) have matching skills, and who get authority and responsibility.

This is done according to attention rules, reflecting the organizational policy, as well as individual preferences for natural idioms of the communication and relations with the sender. When there is no clear decision for selecting among the communications, a random choice among communications in the in-tray will be made. Thus, the recipients of communications may process or ignore it, depending on the attention rules, the priority of the communication and their current work-load. During the simulation various verification activities take place at scheduled intervals, as set by the project policy for quality assurance. Typically this schedule may mandate self-checks every week, peer-reviews every month, and formal quality-auditing at project mile-stones. Similarly, coordination between given parts of the design team has a specified intensity depending on the design task complexity, the skills and experience of relevant actors, and the policy for communication in the project team. There are also formal coordination activities scheduled throughout the project period. Typically these include project meetings at specified mile-stones during project execution (such as 30%, 60% and 90% completeness).

The requests for verification activities are modeled as communication to relevant actors (typically sent as a memo). Verification activities are carried out automatically when the actor acknowledges receiving the request for verification (i. e. accepts the responsibility). The probability that verification activities fail depends on the interdependency of design requirement and solution (verification complexity), whether actors in the ongoing design activity have the required skills, as well as on any previous coordination failures in the design process. In the case of non-conformances (verification failures) decisions are made according to verification rules. Normally this involves corrective action (doing re-work), which must then be completed satisfactorily before relevant design activities can proceed. If the failed activity is not on the critical path, this only affects project economy (i. e. more personnel hours). However, if the activity is on the critical path, corrective action affects both project schedule and economy. If the project is falling behind the acceptable schedule (set by performance requirements), non-conformances are ignored. Ignoring non-conformances will affect the expected design quality. The alternative outcomes of verification failures are summarized in figure 3.7.

The requests for coordination activities are also modeled as communication. Team members must respond to coordination requests to signal their attendance. Coordination requires attendance of actors with required authority and skills in order to be successful. In case of coordination failures, the required action is determined by coordination rules. Normally the coordination activity is rescheduled. This involves rescheduling the coordination meetings, which must be successfully completed before relevant design activities can proceed. If the coordination activity is not on the critical path, this only affects the project economy (more personnel hours). If the activity is on the critical path, however, rescheduling affects both project schedule and economy. If the project is

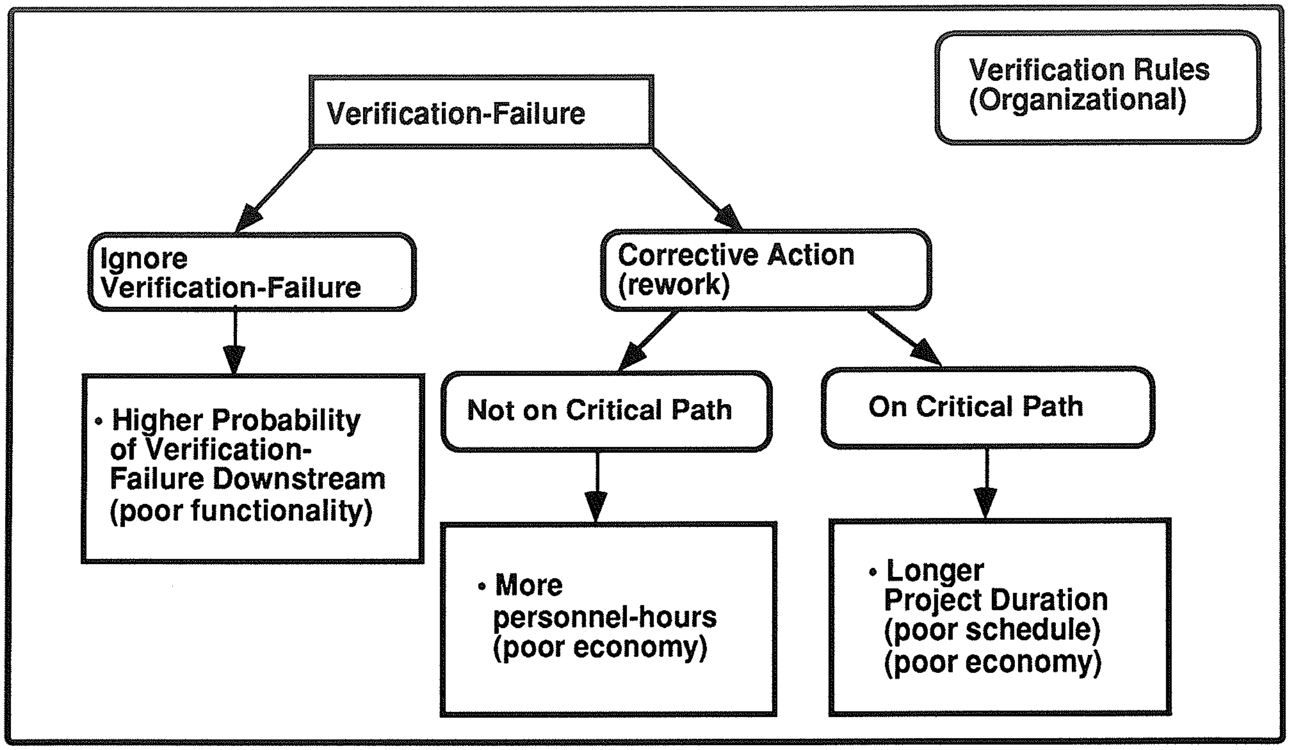

Figure 3.7 Failure in Verification is handled according to verification rules

Verification failures are determined stochastically, based on the failure probability of verification activities. If a verification failure occurs, the project team member with relevant authority must make a descision on whether to take corrective action or ignore it . Normally, the project policy will dictate corrective action (rework). This has more severe effects if the verification failure is associated with design activities which are on the critical path. If the project does not meet its schedule performance criteria, the project policy may dictate that verification failures should be ignored. This increases the probabililty of downstream verification failures, and leads to poor functionality.

falling behind the schedule more than allowed by the performance criteria, then coordination failures are ignored. This increases the probability of verification failures downstream, since the design process will be less controlled. Thus this will affect the expected design quality. In addition, failure to attend completed coordination activities decreases the efficiency of those actors who did not attend (and thus also affects the project economy, and potentially the schedule).

For a closed loop organization design system this reasoning may be extended by including rules for performance comparison, which will alter the organizational policy (verification and coordination rules) during simulation in order to correct emerging problems in project team performance during simulation. The user is included in this loop, to decide what changes to make in order to address the performance issues identified in the current simulation.

3.4 Validation of the model and testing of the predictions

A testable hypothesis arising from the above model is that for a given design project we can model the extent to which there is (1) a set of suitable organizational relations between members of the design team, (2) a match of communication tools between actors in terms of idiom type, and (3) adequate bandwidth of communication between actors. This allows us to make predictions about the verification and coordination quality of the design process, based on simulation of information processing.

In order to test this hypothesis, a test program will be described, carried out and evaluated. The purpose of the test program will be to (1) demonstrate the model's ability to describe the real world, (2) validate qualitative behavior of the model versus established theory, and (3) perform qualitative testing. The testing will be based on modeling and simulating selected design projects. The results from simulations will be compared with theoretical predictions, observations from the design project and interviews with design team members.

The project currently under study is a project to extend the capability of an existing electrical substation project, carried out by the engineering unit of a major westcoast power utility company [Christiansen 91], [O'Brien 92]. The project budget is $ 8 million, and the duration 21 months from October 1990. Thus the substation was joined to the power grid on May 15, 1992. The design project schedule plan (Gantt charts) includes 93 design items (activities). The project involves concurrent design, procurement and construction, which places stringent requirements on the schedule, and thus on verification and coordination. These requirements are even more important since the construction site is situated some 200 miles away from the design office. Functionally however, the modeling of an electrical substation is reasonably simple, as indicated in figure 3.1 above.

The study of the project so far has involved observing the design project team, and a visit to the construction site. Future study will examine the operation of the substation to identify functional non-conformances. This involves interviews with the project leader and project team members to assess the verification and coordination process. The project team and design process will be modeled. A set of qualitative tests will be performed to compare simulation results with
(1) predictions from organization theory (to test the model, and validate its qualitative behavior),
(2) observations from design process (as qualitative testing against real world design project), and
(3) opinions from project team members (in cases where no real world test case is available).

The test examples will address problems in verification and coordination. By modeling changes in information processing tools and behavior, as well as changes in organization structure, the effect on project team performance will be assessed. Examples of possible validation tests are given in figure 3.8.

Test Example 1

Problem:
Inefficient sharing of CAD-data using paper drawings in communication between design office and construction site

Reason:
Inefficient communication between nodes because of insufficient bandwith of communication channels and mismatch in idiom type

Test case:
Introduce CAD-system and communication-link on site

Prediction:
Improved communication should lead to fewer verification failures

Measurement:
Difference in number of verification failures during simulation

Test Example 2

Problem:
Coordination between electrical and telecommunication subteams, first subteam to finish drawings "throws them over the wall"

Reason:
Inefficient organizational relations between nodes

Test case:
1) Introduce 3-D CAD system with shared product model for all disciplines
2) Allow (or force) much wider lateral relations (meetings or liaison role)

Prediction:
Improved coordination quality should lead to fewer coordination failures

Measurement:
Difference in number of coordination failures during simulation

Figure 3.8 Examples of qualitative tests cases for model validation

4. Research Plan

This chapter outlines briefly the plan to complete the proposed research. The schedule is given in section 4.1. Issues regarding the implementation environment are discussed in section 4.2.

4.1 Schedule for the proposed research

The research so far has been preparatory studies (leading to this proposal) from October 1991. Also a field study of the Table Mountain substation project has been carried out since December 1991. The anticipated progress to complete the proposed research is illustrated in figure 4.1. This indicates the times for carrying out the various stages of the proposed research, including

(1) Further development of the model for verification and coordination in design projects. To be carried out in the summer of 1992.
(2) Implementation of a (simplified) prototype of the model. To be carried out in the summer of 1992
(3) Testing and refining the model and implementation against relevant theory and the Table Mountain design project. To be carried out autumn 1992, winter 1993 and spring 1993.
(4) Implementation of a refined model of verification and coordination in design projects. To be carried out in the winter of 1993, and validated in the spring of 1993.
(5) Writing doctoral thesis. To be carried out autumn 1992, winter 1993, spring 1993 and summer 93.

Thus completion of the proposed research is anticipated by the end of the summer quarter of 1993.

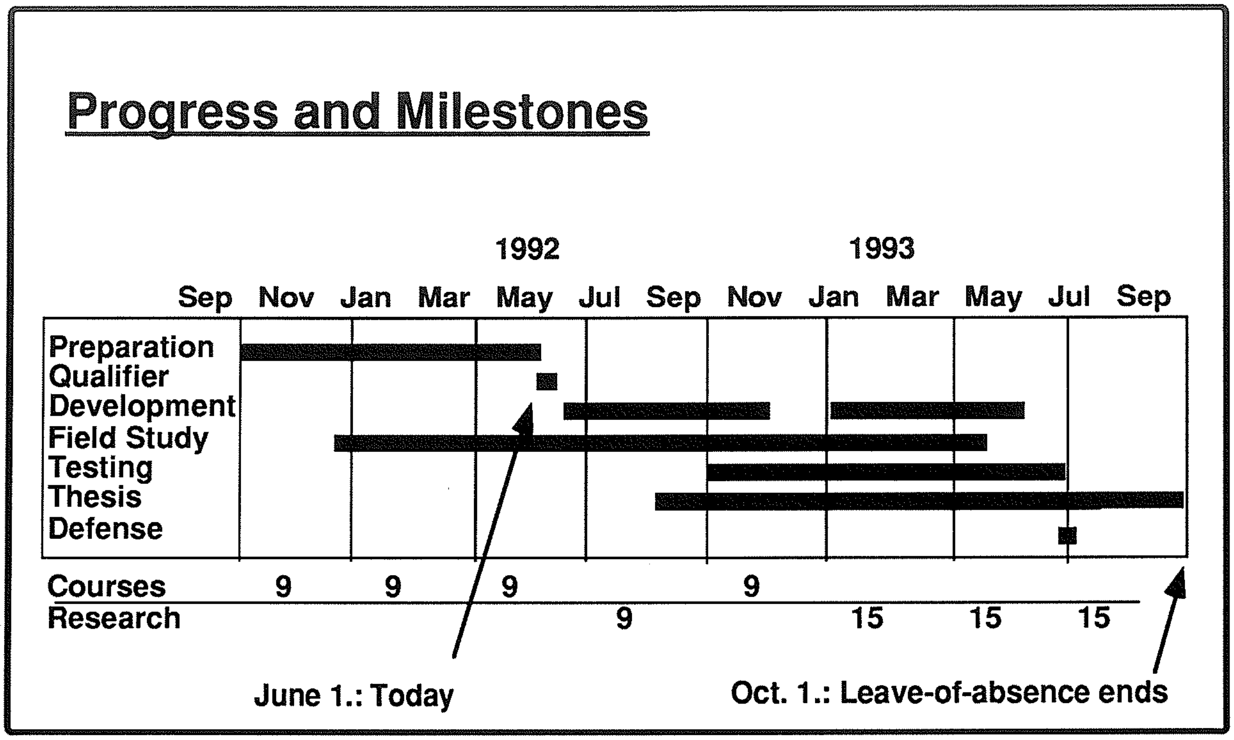

Figure 4.1 The expected schedule to carry out and complete the proposed research

4.2 Issues regarding implementation environment

The implementation of the conceptual model will be made using a knowledge-based development environment. Simulation of information processing requires facilities not normally found in commercial AI development shells, such as a clock and a calendar function. These may be built on top of commercial tools, or alternatively be made available by using a simulation environment .

An example of a simulation environment built using the knowledge engineering principles is the SimKit environment, built on top of the KEE knowledge engineering environment [Intellicorp 88]. A possible future implementation makes use of a distributed AI framework such as i-Agents [Jin 92]. Both Simkit and i-Agents are implemented on top of KEE [Intellicorp 88], which is based on Lisp. Future implementations may be made in a C-based Object Oriented Programming (OOP) environment, such as ProKappa [Intellicorp 91]. This will facilitate wider use.

5. Contributions of the Dissertation

The deliverables expected to result from the proposed research will consist of

(1) A conceptual model of the verification and coordination process in design projects, which can be used to describe and predict design team performance.

(2) A testable implementation of the model for discrete event simulation.

(3) A set of tests to validate the predictions from the model qualitatively against (a) established theory, (b) synthetic experiments (which reflect aspects of design decision-making) and (c) empirical results from a real world design project.

An important contribution of the dissertation resulting from the proposed research will be that it advances our understanding of the interaction between the "quality" of the design team organization and the "product quality" of its design outputs. This ability to analyze organization structures and communication tools used in design projects will contribute towards improving our understanding of the needs for concurrently designing the design process and design project organization.

Another contribution of the dissertation will be to develop a conceptual framework of verification and coordination processes in design, which may be calibrated and further developed by future researchers. The nature of organizations make it difficult to perform organizational studies in a systematic and testable manner. To quantitatively test the predictions from the proposed research will require extensive calibration against a series of real world design projects. In order to allow future research to perform such tests systematically, the model developed will agree qualitatively with established theory. The model will be logically implemented and well documented, making it possible for future researchers to build on the dissertation, model and model implementation for further studies. Together, this work will rectify some of the previously identified shortcomings of the state-of-the-art in studying the performance of project organizations (see chapter 2).

The long term impact of the proposed, and subsequent, research on the social sciences will be towards advancing the formality of social science theories. The impact on technology will be to contribute towards enhancing the performance of construction (manufacturing) organizations.

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